Model XT-100K) and transmitted to a leased transponder on the SBS-6 satellite at 99° W longitude. Transmission was via a CD Radio operated 5.6 M diameter Ku-band antenna (RSI Model 551KS) located on the roof above its offices at 1001 22nd Street NW in Washington, DC. The uplink power level was set to obtain approximately half transponder power or 47 dBW EIRP for the Washington, DC area.

The CD Radio satellite carrier signal is received at the rooftops in the northern Virginia suburbs of Washington, DC at Ku-band (11.7-12.2 GHz) via a 1.8 M diameter antenna. It is then down-converted and retransmitted, without demodulation, at a frequency in S-band (2310-2360 MHz). For frequency diversity in our terrestrial emulation four transmit frequencies, 2322, 2330, 2338, and 2346 MHz were used. Transmitter output power at S-band was set to a nominal 1 W which corresponds to the equivalent of the transmit EIRP from the proposed CD Radio geosynchronous satellites.

The rooftop to mobile link was designed to emulate as closely as possible the CD Radio satellite DARS signal. Look angles, received power level, bandwidth and modulation of a satellite DARS signal were all emulated as closely as can be done by a terrestrial transmitter. In this terrestrial emulation, look angle to the transmitter and signal level will both change more rapidly than with the satellite transmitter.

A block diagram of the CD Radio Signal Distribution and Transmission equipment is shown in Figure 3-4. A photograph of the satellite up link is shown in Figure 3-5.

The rooftop Ku-band to S-band transponder units were designed and built for CD Radio by ICTI of Gaithersburg, MD. These units operate unattended on the rooftops in the test range. Each installation consists of fixed 1.8 M diameter Ku-band antenna, a tunable transponder with 5 W (maximum) S-band transmitter contained in a weather proof case, and an omni-directional S-band antenna mounted at the top of a 20 foot mast.

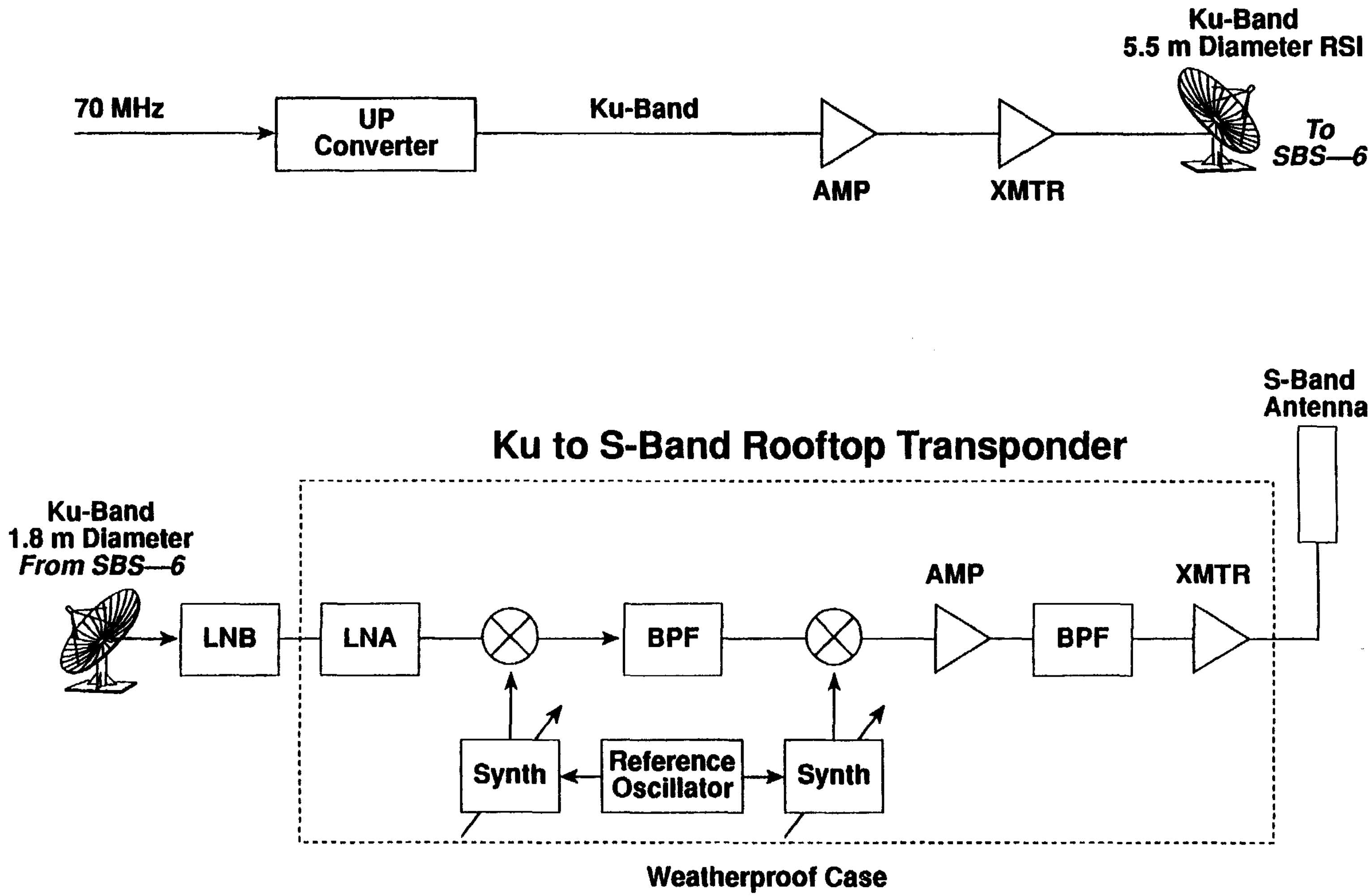


Figure 3—4 Signal Distribution and Transmission Equipment — Block Diagram

Figure 3-5 Satellite Up Link Facilities

A link budget for the S-band and Ku-band links are contained in Attachment A3 of this report. The terrestrial S-band rooftop-to-automobile segment of the experiment link budget is equivalent to that of the proposed CD Radio DARS geosynchronous satellite-to-automobile link. The Ku-band link was conservatively designed with a large power margin. This virtually eliminates its contribution to the S-band mobile link bit error rate.

3.3.4 Mobile Equipment

The CD Radio mobile receive equipment consists of a diversity receiver, baseband processor, audio amplifiers, and operator's panel configured for mounting in an automobile. A set of data collection equipment is included in the automobile to log system performance information. All equipment except the antenna and operator's panel are mounted in the automobile trunk. The CD Radio mobile equipment block diagram is shown in Figure 3-6.

The CD Radio mobile vehicle receives its signal in S-band via a small low gain satellite planar array antenna developed by Seavey Engineering Associates. A photograph of the antenna is shown in Figure 3-6. This antenna is a prototype unit that is representative of the antenna technology currently being planned for implementation. The antenna is omni-directional in azimuth and utilizes left hand circular polarization. Physically the antenna is a 1.88 inch diameter microstrip device fabricated on a ceramic substrate approximately 0.1 inch thick. The nominal antenna gain is 3.0 dBic at 35° elevation angle with a 3 dB elevation beamwidth of 40°. The antenna was flush mounted within the car roof in the horizontal section to the rear of the sun roof mechanism.

The received S-band signals are down-converted to L-band and connected to four trunk mounted modified VSAT receive only units (Comstream Model DBR401). Each receiver recovers the digital bit stream, performs de-interleaving, passes the resultant bit stream through a rate 1/2 Viterbi decoder and de-multiplexes the processed bit stream. The performance of each receiver is monitored by a computer mounted in the car trunk and

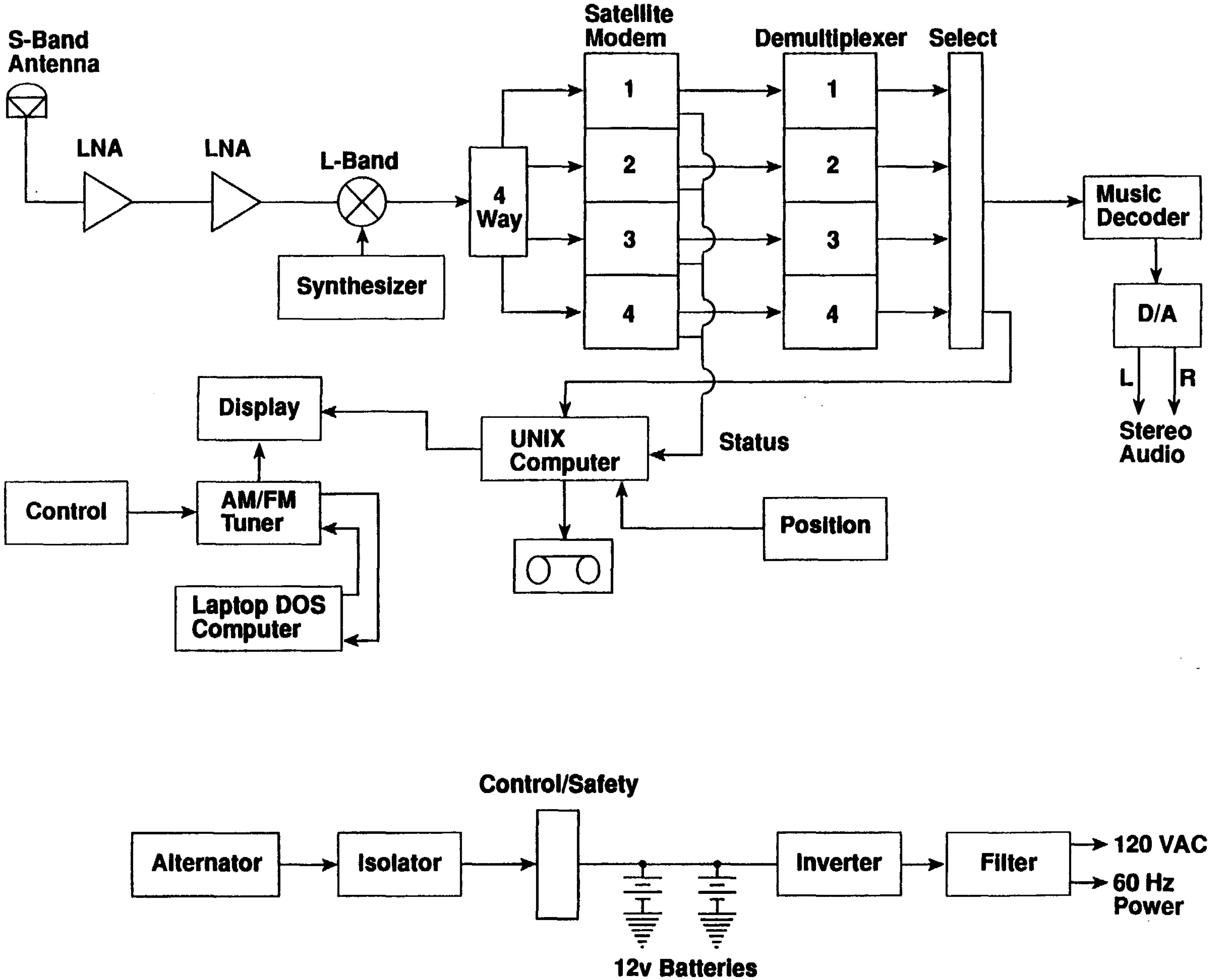


Figure 3–6 Mobile Equipment Block Diagram

one receiver output is selected as the data source. The de-multiplexed 128 kb/s digital bit stream from the selected receiver is applied to a single real time PAC stereo music decoder. The PAC digital output is converted into an analog stereo pair by a dual channel portable reference standard D/A converter (Apogee Model DA1000). The analog stereo signal is then directly connected to the car audio system CD changer input for distribution within the automobile. Photographs of the mobile equipment are shown in Figures 3-7 to 3-10. The CD radio experiment depended heavily on customized and prototype equipment. This equipment needs to be productized and miniaturized for the actual service.

The performance of the four VSAT receivers is logged to control receiver selection and to quantify system operation in the mobile environment. The trunk mounted computer monitors the lock status, Eb/No and AGC data from the four VSAT terminals. VSAT receiver performance information is stored in the trunk computer and annotated with both location and time data .

3.3.5 Prototype Car Radio

The test vehicle was received with a Ford Electronic Division AM/FM/Stereo Cassette premium sound system with JBL audio and CD changer. The Ford Electronics Division factory car audio equipment was modified to operate within the CD Radio satellite DARS system. Control functions were added to operate with satellite DARS and the dashboard display was expanded for music selection information. The resultant car radio has the look, feel and function of the CD Radio system including controls and display. Figure 3-9 shows the CD Radio unit operating in the car dash board in CD Radio mode.

For the CD Radio experiment, driver control over the system in the AM and FM modes is identical to that contained in the car owner's manual. The left side of the car radio display is used in all modes, while the right side of the display is used only in the CD Radio mode. The CD Radio mode is entered by depressing the button marked "CD RADIO" at the left side of the radio front panel. The front panel display shows "CH XX" on

Figure 3-7 CD Radio Mobile Receive Antenna

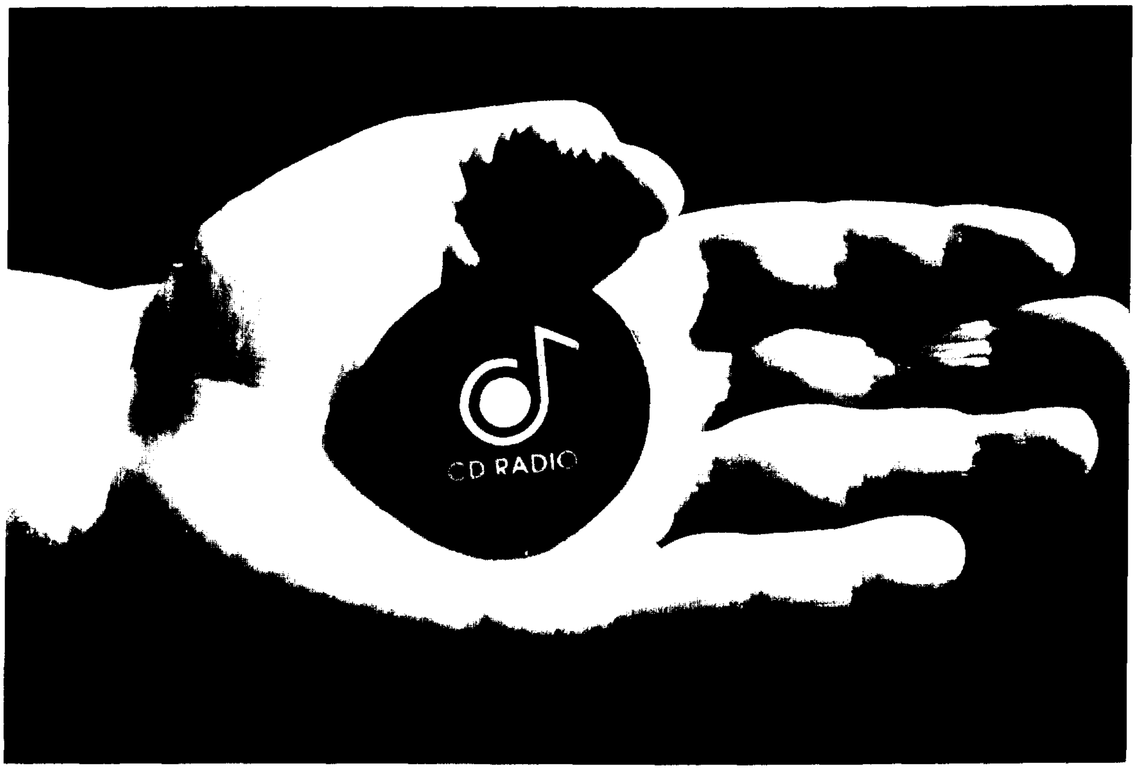


Figure 3-8 CD Radio Mobile Vehicle, Satellite Receivers Installed

Figure 3-9 CD Radio Mobile Vehicle, Full Equipment Installation

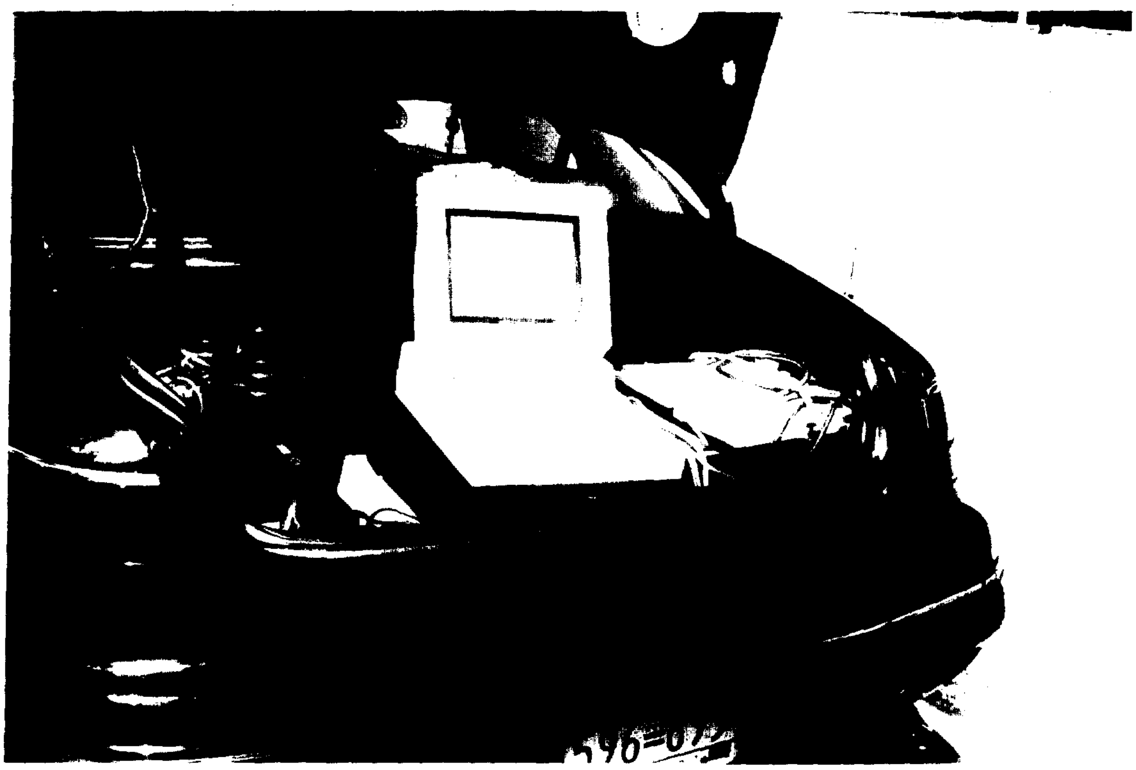


Figure 3-10 Prototype Car Radio for Satellite DARS

the left side and either channel type or artist/title on the right side., where XX (1 - 30) is the CD Radio channel number. In the CD Radio mode digital music is connected directly into the car audio system through the CD player audio input. The standard front panel alpha-numeric display was doubled in physical length to present CD Radio programming information in two lines of 16 characters each. The front panel controls were modified to reflect the CD Radio driver-radio human interface. The stereo cassette player and CD changer were removed for simplicity and to conserve space.

CD Radio implemented many radio functions motorists expect to find in high end car radios. In the CD Radio mode the car radio performs the following functions:

SEEK	The Seek function allows the driver to slew quickly to another channel. Depressing the "SEEK" button causes the radio to slew rapidly up or down through the 30 music channels while displaying channel format. Sound is inhibited during seek.
PRESET	The Preset function allows the driver to pre-select up to 6 favorite CD Radio channels. Channels are pre-selected by tuning to a channel and holding in one of the six numbered buttons for 2 seconds. The display then blinks to confirm selection. Depressing one of the numbered buttons immediately selects the pre-set channel. Pre-set selections are stored through radio power down and operation in other modes.
SCAN	The Scan mode allows the driver to tune through the 30 music channels and obtain a brief 3 second sound sample. Depressing the "SCAN/TUNE" button causes the radio to sequentially tune up through the 30 music channels and dwell on each channel for 3 seconds. During the dwell the driver will hear a short segment of that channel's sound. The Scan can be stopped on any channel by depressing the

"SCAN/TUNE" button a second time. The right hand portion of the radio display shows either channel format or artist/title.

DISPLAY In the CD Radio mode the driver may request an increasing level of detail on the music selection being played. The right hand portion of the radio display presents the driver with four information screens: channel format; artist/title; album title; and, CD catalog number. The initial default CD Radio display is channel format. Additional music selection information is obtained by depressing the button marked "CD RADIO." The first screen shows title and artist, depressing the button a second time provides album title and depressing the button a third time provides CD catalog number. The display returns to the default display from any of the other displays after 2 seconds. The driver may also select artist/title as the default display by depressing and holding the "CD RADIO" button for 2 seconds.

3.3.6 Automobile Modifications

The test vehicle, a Lincoln Mark VIII manufactured by the Ford Motor Company, was adapted to work with the CD Radio mobile equipment. The car audio, power, and climate control systems were modified. CD Radio engineers mounted a 1200 W capacity AC power system in the car trunk to power the satellite DARS receivers plus the data acquisition and test equipment. The AC system is capable of sustained support of the satellite DARS receivers. With input from its two high capacity 12V batteries, the AC power system provides a minimum of 2-3 hours operating time for the the full set of data acquisition and test equipment. The climate control system was reconfigured to provide cooling for the equipment mounted in the trunk.

The S-band satellite receive antenna was embedded in the car roof and connected to the trunk mounted receiver equipment. The car roof was then re-finished completely hiding the presence of the antenna.

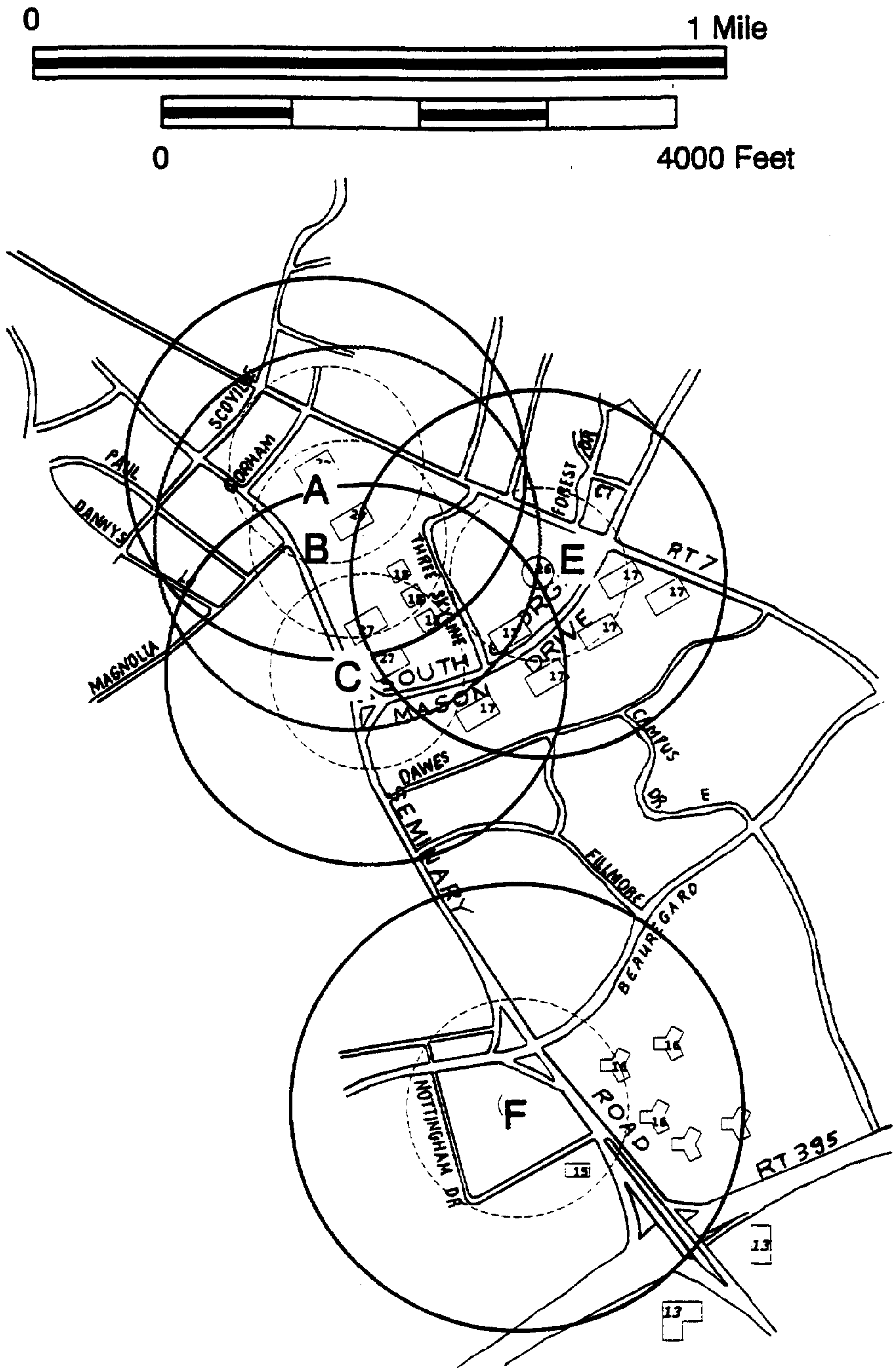
3.3.7 Test Site

System tests were conducted in the Washington, DC metropolitan area using a group of terrestrial transmitters emulating the geometry and signal characteristics of a geosynchronous satellite DAR system developed by CD Radio. A closed circuit road segment meeting the following criteria was selected:

> Inside the perimeter of the Washington beltway and easily accessible from downtown;
>
> A sufficient number of buildings 20 stories in height or taller spaced 0.1 - 0.2 miles apart so that at least two buildings are in view at all times;
>
> Representative of urban/suburban/interstate routes;
>
> Segment must take at least 5-10 minutes to traverse; and
>
> Presence of an overpass is desirable..

The selected test area is south of Washington, DC, east of Interstate 395 and mid-way between the 14th Street Bridge and the Beltway. A site plan showing the location of the roof-top transmitters is shown in Figure 3-11. The area has several 30 story buildings near the road and is close to downtown Washington, DC. It is representative of the national interstate highway system and the urban/suburban commuting environment. A detailed description of the test site is contained in Attachment A3 of this report.

Figure 3-11 CD Radio Test Site Plan



4. TEST RESULTS SUMMARY

4.1 INTRODUCTION

In this satellite DARS experiment, CD Radio has successfully demonstrated the operation of its system in a representative environment at the S-band frequencies allocated at WARC 1992. The test results support all CD Radio test objectives as listed in Section 2 of this report. With the results of this experiment CD Radio has shown:

- Satellite spatial diversity significantly reduces blockage;
- Satellite spatial and frequency diversity mitigates multipath;
- The sound quality of 128 kb/s audio compression;
- The suitability of a small low gain omni-directional receive antenna;
- A bandwidth of 8 MHz will support 30 channels of stereo music; and,
- Interference at S-band is inconsequential.

These results show that CD Radio's system design is technically sound and can be implemented.

4.2 TESTS PERFORMED

Initial testing began in a data only mode. In this preliminary phase the signal source, distribution, and transmission equipment were tested The mobile diversity receiver was then added and performance data collected on the demonstration system through to the receiver output. The test area was calibrated for signal strength to ensure an accurate satellite simulation and proper signal reception. A representative highway overpass was instrumented to measure the amount of signal blockage.

The music processing equipment was then added plus the car receiver control panel and the entire test system fully tested. Signal processing algorithms for compression, encoding and interleaving were tested.

During all test runs the trunk mounted computer monitored and logged the performance of the satellite DARS receivers. Status data were recorded from each receiver every 100 msec and whenever a receiver drops lock. Each data sample was recorded on digital tape as a 20 byte record containing the following information:

Time	HH:MM:SSS
Receiver Number	X
Location	XXXXX
EB Status	XXX
AGC Status	XXX
Lock Status	X

Where the components of the data block are defined as follows:

Time:	Time the data sample was collected to the nearest 1/10th of a second;
Receiver Number:	Satellite modem ID, 1 - 4;
Location:	Distance driven on test path;
EB Status:	Satellite modem Viterbi decoder error count
AGC Status:	Satellite modem AGC level, 1 -255
Lock Status	Satellite modem status, "N" for no lock, "D" for demodulator lock and "V" for Viterbi lock.

4.3 TEST RESULTS

4.3.1 Highway Overpass Test Results

Service continuity of a single satellite DARS system will be disrupted by blockage between the satellite and mobile vehicle receiver. Specific concern has been focused on overpasses since they are extremely numerous in suburban areas and are significant in number in many rural areas. The number, frequency and length of such outages would cause disruptions in service with a sufficient frequency to be annoying for music listeners. CD Radio's innovation of satellite spatial diversity significantly reduces such disruptions. An experiment was conducted to obtain measured data showing that analytical calculations of such blockage avoidance by satellite spatial diversity are accurate representations of actual system performance.

The experiment shows that the CD Radio DARS satellite system using satellite spatial diversity will provide large reductions in service outages due to overpass blockage as compared to a satellite DARS not using spatial diversity. The measurement data show:

> Overpass blockage avoidance in a satellite spatial diversity system can be calculated using the physical geometry and the actual satellite DARS system performance will be virtually identical.
>
> No anomalous propagation effects were noted in the experiment.

Reference should be made to Attachment A1 paragraph A1.1 for detailed highway overpass test results.

4.3.2 Multipath Fading And Blockage Test Results

Service continuity of a single satellite DARS system will be disrupted by signal fading between the satellite and mobile vehicle receiver whenever the faded signal level is less than the receiver's threshold. The number, frequency and length of such outages would cause disruptions in service with a sufficient frequency to be annoying for music listeners depending on the DARS system transmission margin. CD Radio's innovation of satellite spatial and frequency diversity significantly reduces such disruptions. An experiment was conducted to obtain measured data showing that satellite spatial and frequency diversity reduce the effects of multipath fading.

The experiment shows that the CD Radio satellite DARS system using satellite spatial and frequency diversity will provide a large reduction in service outages due to multipath fading as compared to a satellite DARS not using spatial and frequency diversity. The measurement data from the CD Radio Test Range show:

> Frequency and spatial diversity reduce the effects of multipath fading in the test system and the actual satellite DARS system performance should be virtually identical.
>
> Frequency selective fading is sufficiently large and occurs often enough that frequency diversity in a DARS satellite system is required.

Reference should be made to Attachment A1 paragraph A1.2 for detailed multipath fading test results.

4.3.3 Sound Quality Results

Sound quality testing with the PAC algorithm operating at 128 kb/s was performed both by CD Radio and AT&T Bell Laboratories. In its internal testing AT&T found listeners perceived that PAC significantly out performed other compression algorithms when operating at 128 kb/s. The results of the AT&T testing are summarized in Figure 4-1. CD Radio performed limited listener evaluation tests with PAC in both a studio and in its test vehicle with similar results. CD Radio audio quality testing utilized a wide variety of narrowcast formats to ensure listener familiarity with the music.

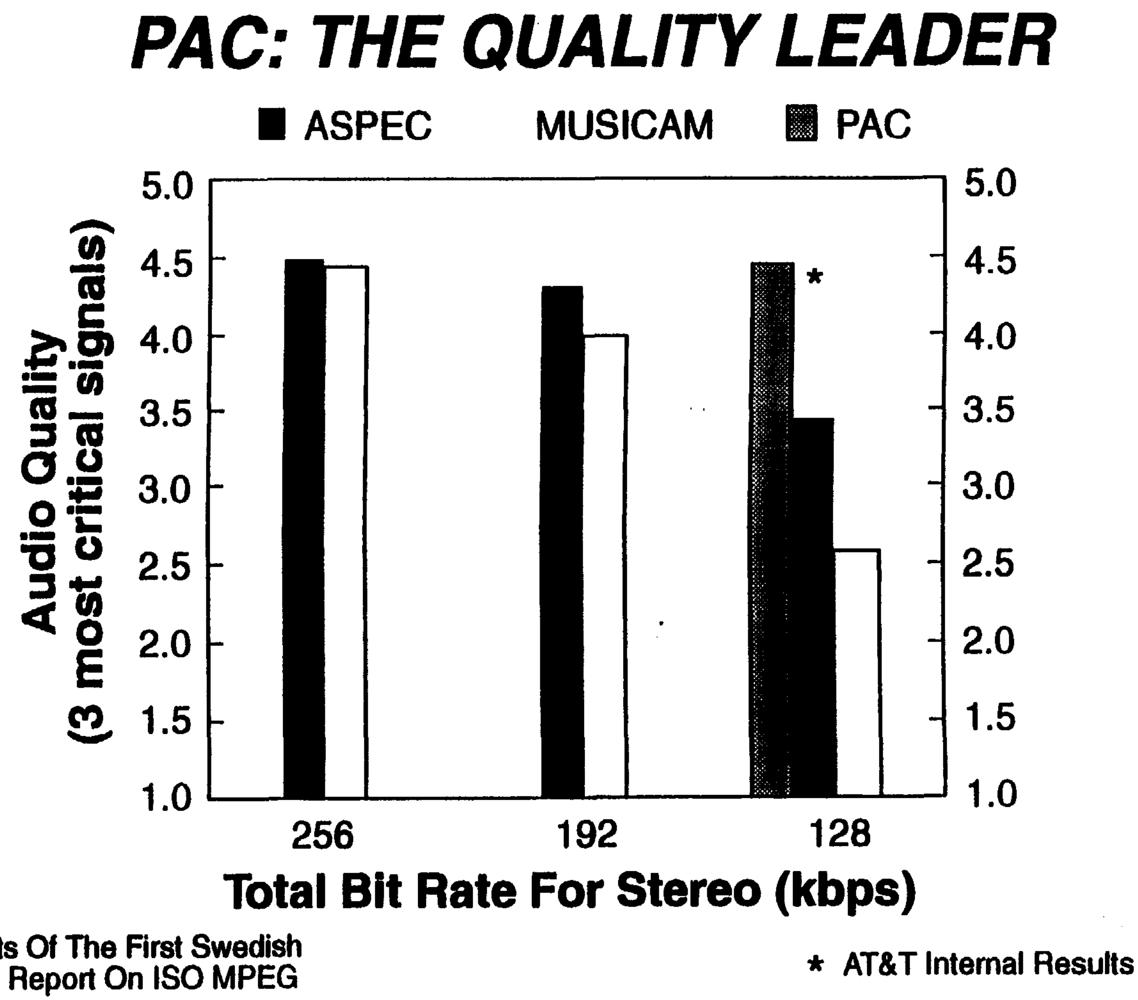


Figure 4-1 AT&T PAC Listener Test Results

4.3.4 Antenna Test Results

The CD Radio small low gain omni-directional receive antenna was subjected to extensive testing. Test results show the antenna generally met all the transmission performance requirements listed in paragraph A3.4 of Attachment A3 and is suitable for use in the CD Radio satellite DARS system. Reference should be made to Attachment A1 paragraph A1.2 for detailed antenna test results.

Tests were performed on both flat and curved ground planes, both with and without auto body filler. Results show almost no change in performance from the flat to curved ground plane. The filler had a repeatable effect on antenna tuning, with the antenna center frequency moving downward after the application of the filler.

4.3.5 Spectral Measurement Results

The satellite signal generated in the CD Radio test system consisted of 31 channels (30 music channels plus one control channel) of data each at a 128 kb/s data rate. These channels were TDM multiplexed into a single 3.968 Mb/s bit stream and convolutionally encoded by a rate 1/2 FEC. The resultant 7.936 Mb/s bit stream was then QPSK modulated on a 70 MHz carrier.

Spectral measurements at 70 MHz were made using an HP Model 8560 E spectrum analyzer. Figure 4-2 shows the spectrum of the transmitted CD Radio signal operating with 30 CD-quality channels of music and one control channel. This signal occupies just 4.7 MHz of spectrum.

In this experiment CD Radio used a rate 1/2 FEC rather than a rate 1/3 FEC as planned for its operational system. Extrapolating the measured bandwidth to a rate 1/3 FEC signal, one calculates 7.9 MHz which is under the design goal of 8 MHz.

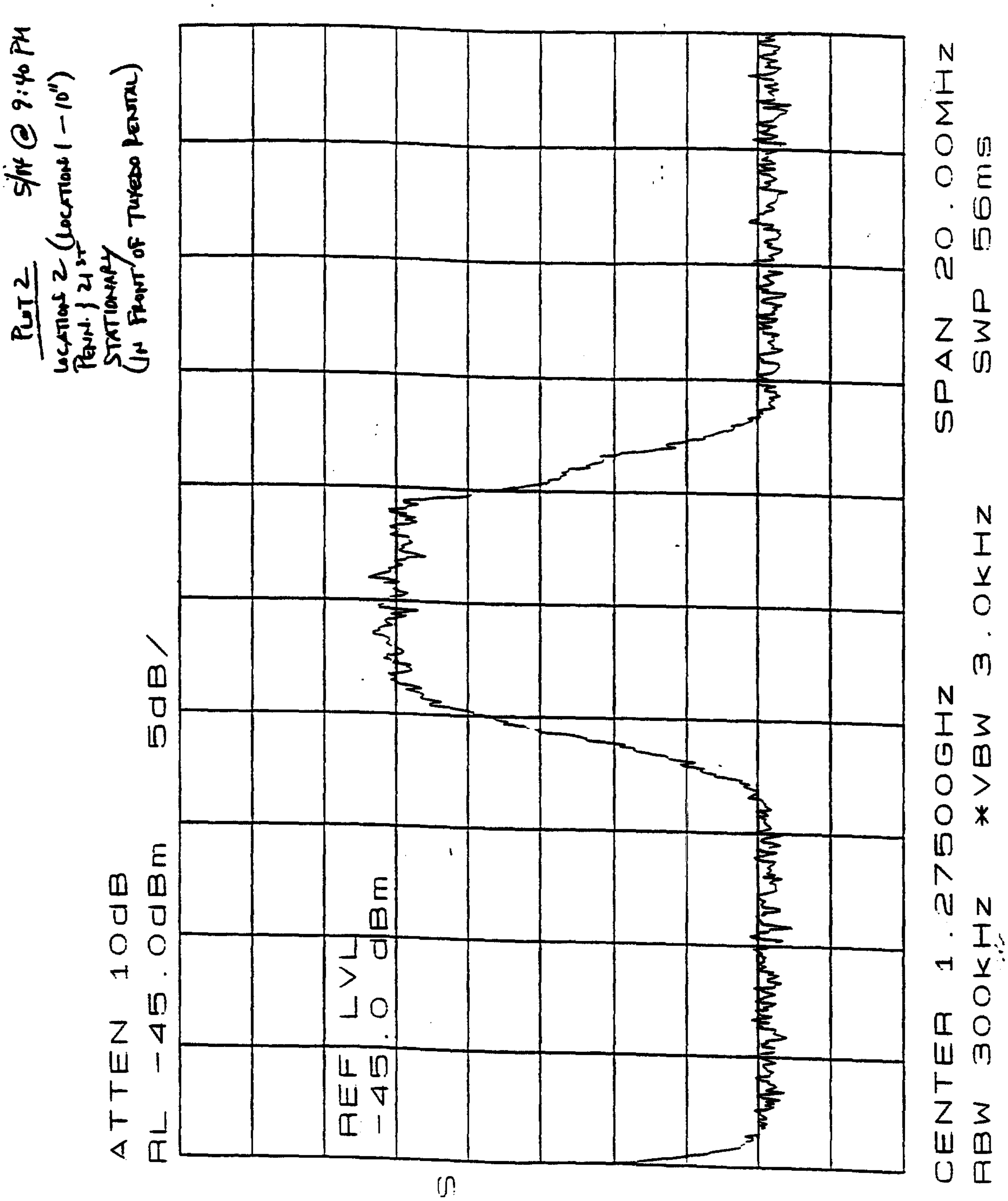
4.3.6 Interference

Throughout its extensive field testing, CD Radio monitored the received 2310 - 2360 MHz S-band signals with a spectrum analyzer for sources of interference. No interfering signals were seen nor were any effects from interfering signals noted.

4.3.7 Operational Results

The operation of the prototype CD Radio satellite DARS automobile receiver was demonstrated to a number of individuals. Survey results indicate that the controls and display features were easy to use and that the advanced features were readily understood. Users found the CD Radio features familiar, easily understood and logically implemented. The channel selection modes were particularly useful in quickly tuning to the desired music format and in storing the driver's frequently listened to channels. Survey results also show the CD Radio display of music information was of real interest. Thus, the prototype CD Radio satellite DARS automobile receiver driver-radio human interface was well received.

Figure 4-2 CD Radio Signal Spectrum Plot, Over Air at VSAT Receiver Input



5. CONCLUSIONS

In its testing CD Radio has:

Demonstrated system operation in S-band in a representative environment;

Showed the improvements obtained by using frequency and spatial diversity reception and advanced channel coding;

Acquired system performance data;

Collected man/machine interface data sufficient for final system.

The results of the demonstration were excellent. From an operational viewpoint, vehicle users praised the transmission quality, the ease of operation and the equipment invisibility. From an engineering viewpoint, considerable data was obtained on equipment performance and propagation. The propagation data showed that the combined spatial, frequency and time diversity provided large mitigation against multipath (greater than 10 dB) and complete avoidance of blockage for the test range utilized. Further testing will be done for other geographically diverse areas and climates.

ATTACHMENT A1

TEST RESULTS

A1.1 HIGHWAY OVERPASS

Objectives

No previous detailed measurement data on the blockage effects of overpasses at microwave frequencies could be found. The main objective was to obtain detailed measurements of overpass blockage for a DARS satellite spatial diversity system operating in the 2310-2360 MHz band. The second objective was to determine if any anomalous propagation effects existed such as knife-edge diffraction, structural returns, ducting, etc. The length of an overpass outage is dependent on the size, height and orientation towards the satellites of the overpass and the vehicle speed. A measurement on a very large overpass at relatively low angles of satellite elevation represents a near worst case in terms of blockage length and of anomalous propagation.

Implementation

The location of a suitable overpass was extremely difficult since, besides the desired large overpass size, two high buildings are required for the S-band transmitters which must be situated so as to provide the needed elevation and azimuth angles. Fortunately, an excellent overpass experimental site was found.

A picture of the overpass is shown in Figure A1-1. The overpass is a divided four lane highway connecting Arlington, VA with National Airport. The site is located in the southern portion of Crystal City which is a typical urban area. The overpass is above U.S. Route 1 which in the site area is a six lane divided super highway. The overpass is approximately 57 feet wide with the bottom 14 feet high and the top 19 feet high. It crosses U.S. Route 1 canted 5° from the perpendicular. One satellite S-band transmitter (hereafter called F1) was located on a building approximately 340 feet away from the overpass with a 15° bearing and elevation angle. The other S-band transmitter (hereafter called F2) was located on a building approximately 295 feet away from the overpass with a 198° bearing and 18° elevation angle.

Measurements

The experiment site was calibrated so that the F1 and F2 signal levels would be relatively constant in the area under and around the overpass and at the same level at the center of the overpass. The transmit levels were set so a dynamic level change in received signal strength of 15 dB could be recorded. This also was useful so secondary anomalous propagation effects could be noticed. The vehicle was driven in both directions on U.S. Route 1. Specifically, measurements were taken of both F1 and F2 every 10 feet on lanes 1 and 3 and lanes 4 and 6.

Results

Figure A1-2 summarizes the results. This figure shows the average of the F1 measurements with a dotted line and the F2 measurements with a solid line along the vehicle drive path. Also shown are the physical location of the overpass and the physical location of blockage outage from a geometrical calculation. The results demonstrate:

> A vehicle equipped to receive both satellite transmitters would have no blockage outage if the receiver either combined the two signals or switched in the vicinity of the 370 foot location.
>
> Geometrical calculations of overpass blockage are accurate representations of satellite DARS outage.
>
> No anomalous propagation effects were found.

Figure A1-1 Highway Overpass, Crystal City, Route 1, Alexandria, VA